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Herwig 7.0/Herwig++ 3.0 release note

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Abstract A major new release of the Monte Carlo event generator Herwig++ (version 3.0) is now available. This release marks the end of distinguishing Herwig++ and HERWIG development and therefore constitutes the first major release of version 7 of the Herwig event generator family. The new version features a number of significant improvements to the event simulation, including: built-in NLO hard process calculation for virtually all Standard Model processes, with matching to both angular-ordered and dipole shower modules via both subtractive (MC@NLO-type) and multiplicative (Powheg-type) algorithms; QED radiation and spin correlations in the angular-ordered shower; a consistent treatment of perturbative uncertainties within the hard process and parton showering. Several of the new features will be covered in detail in accompanying publications, and an update of the manual will follow in due course.

1 Introduction

Herwig is a multi purpose particle physics event generator. It is based on the experience gained with both the HERWIG [1] and the Herwig++ [2] event generators. The latest version of Herwig++, 3.0, marks the point at which the physics capabilities of the HERWIG version 6 series are fully superseded, and thus the last point at which their development is distinguished. Herwig++ 3.0 will henceforth be known as Herwig 7.0. It replaces any prior HERWIG or Herwig++ versions.

Herwig provides highly improved and extended physics capabilities compared to both its predecessors, in particular the ability to perform simulations at next-to-leading order in QCD, while keeping the key physics motivations such as coherent parton showers (including both angular-ordered and dipole evolution), the cluster hadronization model, an eikonal multiple interaction model, and highly flexible BSM capabilities.

The last major public version (2.7) of Herwig++ is described in great detail in [2–7]. This release note summarizes the major changes and improvements introduced since then, which constitute the base for the Herwig 7 series. The physics questions addressed by the capabilities of Herwig 7 will be covered in detail in accompanying publications, as well as comparisons with the other well-known general-purpose event generators, Pythia [8,9] and Sherpa [10]. A detailed manual covering all technical aspects will be prepared in due course. Please refer to [2] and the present paper if using Herwig 7.0.

1.1 Availability

The new program version, together with other useful files and information, can be obtained from the web site <https://herwig.hepforge.org/>. In order to improve our response to user queries, all problems and requests for user support should be reported via the bug tracker on our wiki. Requests for an account to submit tickets and modify the wiki should be sent to herwig@projects.hepforge.org.

Herwig is released under the GNU General Public License (GPL) version 2 and the MCnet guidelines for the distribution and usage of event generator software in an academic setting,

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which are distributed together with the source, and can also be obtained from <http://www.montecarlonet.org/>.

1.2 Prerequisites

Herwig 7.0 is based on ThePEG 2.0, which is available along with the Herwig installation sources at <https://herwig.hepforge.org/downloads>. Further requirements are BOOST [11], gsl [12], fastjet [13] and LHAPDF [14], while a number of other dependencies are necessary in order to fully exploit the program's capabilities. Amongst these are HepMC and/or Rivet [15] to analyze simulated events, as well as some or all of the external amplitude libraries discussed in Sect. 2.2.

In order to simplify the installation process, we provide a *bootstrap* script to facilitate a consistent build and installation of Herwig in a convenient way. The script requires a python installation, and is available from <https://herwig.hepforge.org/herwig-bootstrap>.

1.3 Documentation

A significant new feature is the online documentation, which has been completely rewritten and greatly extended to reflect the major changes introduced with this version and replaces the wiki pages. It can be found at <https://herwig.hepforge.org/tutorials/>. An update of the more detailed physics and manual will be made available in a similar format in due course. Code snippets are provided for a wide variety of control functions for easy inclusion into input files. Detailed documentation of the source code and input file interfaces generated with doxygen is available at <https://herwig.hepforge.org/doxygen/>.

2 NLO event simulation

A key ingredient in the design and development of Herwig 7.0 was to provide event simulation at next-to-leading order (NLO) accuracy in the strong coupling *by default* for as many Standard Model processes as possible in an automated way. The program, with the help of external libraries used for amplitude calculation, is now able fully automatically to assemble NLO QCD corrections to virtually all Standard Model processes, including matching to both of its parton-shower algorithms [16, 17], via methods inspired by either the MC@NLO [18] or Powheg [19] type algorithms, which we refer to as subtractive and multiplicative matching, respectively.

Based on extensions of the previously developed Matchbox module [20], NLO event simulation is now possible without the requirement of separately running external codes and/or dealing with intermediate event sample files. Slight

changes have been made to improve Herwig's steering at the level of input files, and significant improvements are provided to integration and unweighting, including parallelization to meet the requirements of more complex processes.

2.1 The matchbox module

The design of the Matchbox modules closely resembles the structure of the NLO QCD cross section calculated within a subtraction paradigm, including the matching subtractions required to consistently combine such calculations with parton showering downstream. Subtraction terms are available in a flexible way, though only Catani–Seymour dipoles [21, 22] are provided so far, including both massless and massive QCD as well as the subtraction terms required for supersymmetric QCD corrections.

Parton-shower matching subtractions are provided on an equally flexible footing, including those required for the angular-ordered shower [16], the dipole shower [17], as well as matrix-element corrected showers forming the basis of Powheg-type matching. For the latter, we provide additional functionality to sample the matrix-element correction Sudakov using the adaptive method outlined in [23]. In order to simplify the calculation of matching subtractions for the angular-ordered shower, the kinematics reconstruction used to work out the final shower kinematics has been changed to avoid additional Jacobian factors when compared to the dipole parameterization in the case of a single (or in general, the hardest) emission.

2.2 External amplitude providers

In order to set up the full calculation of a cross section, Matchbox requires plug-ins to provide the respective tree and one-loop amplitudes. These plug-ins can be interfaced either at the level of matrix elements squared (or tree-loop interferences, respectively), or at the level of helicity, colour-ordered subamplitudes with both trace- and colour flow bases provided within the Matchbox core through adapted versions of the ColorFull [24] and CVolver [25] libraries.¹ While we provide built-in amplitudes for a limited number of processes, the bulk of Standard Model processes can be simulated using external amplitude plug-ins.

Based on extensions of the BLHA standard [26, 27], Herwig currently supports interfaces to GoSam [28], MadGraph [29], NJet [30], OpenLoops [31] and VBFNLO [32, 33]. Amplitudes for a limited number of LHC relevant processes are directly provided along with the release, and amplitudes for electroweak Higgs plus jets production are

¹ Other choices of colour bases are straightforward to implement through a very transparent interface.

available from the **Matchbox** plug-in **HJets++**, which is available in the **Contrib** section of the **Herwig 7.0** release.

2.3 Electroweak corrections to VV production

Electroweak corrections to the production of heavy vector boson pairs have been computed [34,35] and implemented into the program, as outlined in [36]. The corrections are applied as an event reweighting factor $K(\hat{s}, \hat{t})$. In order to apply this correction in a meaningful way one has to ensure that additional QCD corrections are not too large and apply reasonable cuts to the final state, as detailed in [36]. The reweighting is straightforward when applied together with Powheg-matched QCD corrections. If subtractive QCD matching is going to be applied one should rather apply the matching on information extracted directly from the leptons in the final state, this is detailed as an alternative method in [36]. In order to apply the method, one has to download grid files for the actual K factors from a [public archive](#) at [hepforge](#).

3 Improvements to the angular-ordered parton shower

This release includes a number of improvements, which finally bring the default angular-ordered parton shower to the same level of accuracy as that in **HERWIG 6**.

3.1 QED showering

The emission of QED radiation was not included in **Herwig++**. In **Herwig 7.0** it is included in the following way:

- A maximum scale is selected for QED radiation in the same way as for QCD radiation, although selecting from the other charged particles in the process rather than the colour partner in order to determine the scale. This scale need not be the same as the maximum scale for QCD radiation.
- Trial QCD and QED emissions are generated and the one with the higher scale selected, as required by the competition algorithm. This branching is generated as before and then any subsequent emissions of the same type are required to be angular ordered² while those of a different type are only required to be ordered. For example if we generate a $q \rightarrow qg$ emission at an evolution scale \tilde{q}_1 and the quark has light-cone momentum fraction z_1 then any subsequent $q \rightarrow qg$ emissions must occur at a scale $\tilde{q}_2 < z\tilde{q}_1$, as required by angular ordering. However, any

² With the proviso discussed below for $g \rightarrow q\bar{q}$ branchings or in the QED case $\gamma \rightarrow f\bar{f}$ splittings.

QED $q \rightarrow q\gamma$ branchings need not be angular ordered and therefore can occur at an evolution scale $\tilde{q}_2 < \tilde{q}_1$.

3.2 Spin correlations in the shower

There are correlations between the azimuthal angle of a branching and both the hard scattering process and any previous branchings that occurred in the parton shower. There are two types of correlation:

1. The soft correlation from the eikonal current, which correlates the direction of the emitted gluon and the colour partner.
2. Spin correlations in the collinear limit between the azimuthal angle of the branching and the hard process and any previous emissions.

Both of these effects are included in **Herwig 7.0** using the algorithm of [37–39]. Now that the full spin correlations are incorporated in the parton shower there is no requirement that unstable decays are generated before the parton shower in order to generate the spin correlations between the production and decay of the particles as described in [40,41]. The decays of unstable fundamental particles are now handled as part of the parton-shower stage of the event generation including all the spin correlations, both between the production of particles and the parton-shower emissions, the production and decay of particles, and the decay of particles and any parton-shower emissions. The spin correlations are switched on by default and can be switched off using

```
set /Herwig/Shower/Evolver:SpinCorrelations No
```

While the soft correlations can be switched off using

```
set /Herwig/Shower/Evolver:SoftCorrelations No
```

we do not recommend this as the soft correlations affect the cluster mass spectrum and therefore this change requires a retuning of the parton-shower and hadronization parameters.

As the spin correlations are currently not implemented in the shower subtraction terms used at next-to-leading order the spin correlations are switched off by default when using NLO matching. However, as we use the same formalism internally as **MadGraph** for the calculation of helicity amplitudes [42] the interface to **MadGraph** can fill the spin-density matrices used in the spin-correlation algorithm and therefore the correlations can be correctly generated at leading order.

3.3 $g \rightarrow q\bar{q}$

The branching $g \rightarrow q\bar{q}$ is only singular in the collinear limit for massless quarks and does not have a soft singularity. It therefore should not be angular ordered in the parton shower,

although given the nature of the parton shower algorithm it must continue to be ordered in the evolution variable. We therefore relax the constraint on this branching so that if a gluon is produced at a scale \tilde{q}_1 with light-cone momentum fraction z_1 the maximum scale of a subsequent $g \rightarrow q\bar{q}$ branching is now \tilde{q}_1 , the maximum allowed by ordering of the evolution variable, rather than $z_1\tilde{q}_1$ as required by angular ordering. The maximum evolution scale for other branchings remains unchanged.

Similarly, the arguments presented in [2,43] that the scale used in the strong coupling for a branching should be the relative transverse momentum, p_\perp , do not apply, and therefore we have changed this scale to be the invariant mass of the $q\bar{q}$ pair for this branching only.³

4 Perturbative and shower uncertainties

Perturbative uncertainties in all of the hard processes provided by the **Matchbox** module can be assessed by variation of the renormalization and factorization scales, respectively. When fixed-order predictions at leading or next-to-leading order are combined with subsequent parton showering, variations of the renormalization and factorization scales in the parton shower (i.e. variations of the scale arguments of α_s and the parton distribution functions) should be performed in a *correlated* way along with variations in the hard process. While independent variations are technically possible to assess patterns of scale compensation, the default uncertainty settings will perform a consistent variation.

In addition to estimating unknown higher-order corrections by variation of the renormalization and factorization scale, genuine parton-shower uncertainties due to missing higher logarithmic orders and phase-space constraints can also be estimated by varying the hard scale in the parton shower. There is no unique definition of such a scale, and the relevant quantity is a specific detail of the parton-shower algorithm and varies considerable between different approaches. We provide variations of the relevant scale in both the angular-ordered and the dipole shower algorithms, which can be used to assess these uncertainties, which are expected to be reduced by use of NLO matched simulations. Specifically for this purpose, easily usable settings of strict leading-order simulation to be compared to improved NLO simulation are provided within the new steering formalism summarized in Sect. 6.

5 Tuning

The improvements to both shower modules, as well as the inclusion of next-to-leading order cross sections, have

required a new tune to e^+e^- data; this tune has been carried out using standard methods based on the **Professor** framework [44] using a representative set of e^+e^- data as previously described in [2]. Similar parameters and an overall reasonable description of the data have been obtained for both the angular-ordered and the dipole shower. The results of these tuning efforts are the default for the **Herwig** 7.0 release.

5.1 Tuning of the multi-parton interaction model

It was shown in Ref. [45] that a good description of both underlying event and double parton scattering data [46] can be obtained if one includes the latter in the data being fit to with a sufficiently high weight. We followed the procedure described in Ref. [45] using the MMHT2014 LO parton distribution function [47]⁴ and obtained a tune consistent with double parton scattering data ($\sigma_{eff} \approx 15$ mb) that also gives a good description of the underlying event data from the Tevatron's lowest analysed energy point [50], $\sqrt{s} = 300$ GeV to the LHC's highest [51], $\sqrt{s} = 7$ TeV.

Herwig 7.0 is released together with the tune H7-UE-MMHT, which it uses by default. More information and other related tunes can be obtained from [the Herwig tunes page](#).

6 Steering, integration and run modes

Owing to the complexity of the processes that can be simulated with **Herwig**, this version introduces some new run modes as well as highly simplified input files to ease steering the event generator. Two alternative integrator modules are provided in addition to the old default, **ACDC** of **ThePEG**, providing superior performance especially for more complex processes. One of the algorithms is based on the standard sampling algorithm contained in the **ExSample** library [23], while the other is based on the **MONACO** algorithm, a **VEGAS** [52] variant, used by **VBFNLO** [32,33].

Since both of these algorithms require an integration grid to be set up prior to generating events, two levels of run mode have been introduced in addition to the old **read** and **run** steps, to meet the requirements of more complex processes. The new **integrate** step performs the grid adaptation; it is possible to parallelize this step in a way that does *not* require inter-process communication and the individual tasks in this parallelization can easily be submitted to standard batch or grid queues. The **integrate** step is to be preceded by a **build** step,⁵ which will assemble the full

³ A similar change has been introduced in the dipole shower.

⁴ In the near future we also plan to provide tunes using CT14 [48] and NNPDF3.0 [49] parton distribution functions.

⁵ The old **read** step is still available, representing the subsequent execution of both the **build** and the **integrate** steps in one step.

fixed-order or matched cross section, including subtraction terms and the possibility of external amplitude libraries generating dedicated code for the process of interest. As this step may also require considerable computational resources, the `integrate` and `run` steps both support reading in additional input files, so-called setup files, to modify run parameters independently of the process of building an event generator object. Detailed examples of these various new workflows are given in the [new documentation](#).

Event generation itself can be parallelized either through submitting runs with explicitly set random seeds or through the newly introduced feature of forking several event generation jobs on multicore nodes.

7 Herwig contrib projects

A number of related codes have been developed along with the main `Herwig` 7.0 development; while these libraries are not supported at the same level as the core `Herwig` release, they are provided along with it. Amongst other tools, the new program version provides the following plug-ins:

7.1 Electroweak Higgs plus jets production

A dedicated `Matchbox` plug-in providing amplitudes for the calculation of electroweak Higgs plus jets production at NLO QCD is available along with the release. This library has been used in the calculation reported in [53]. It provides a full calculation of $pp \rightarrow h + n$ jets at $\mathcal{O}(\alpha^3 \alpha_s^{n-2})$ for $n = 2, 3, 4$ at leading, and $n = 2, 3$ at next-to-leading order QCD. All relevant topologies of either VBF or Higgs-Strahlung type are taken into account along with all interferences. The technical details of the library will be described elsewhere; its use is the same as for all other `Matchbox`-based calculations and a corresponding input file snippet to enable this class of processes is provided.

7.2 FxFx merging support

`Herwig` 7.0 contains interface support for FxFx merging [54], a method for merging multi-jet NLO samples with a parton shower. The interface allows usage of samples generated from `MadGraph 5/aMC@NLO` [55]. The module has been tested for $W +$ jets and $Z +$ jets events, and compared against LHC data at 7 and 8 TeV [56]. Other processes will be supported in future releases.

7.3 Higgs boson pair production

The `HiggsPair` and `HiggsPairOL` packages offer production of Higgs boson pairs via gluon fusion. The former uses code

from `HPAIR` [57, 58] whereas the latter uses the `OpenLoops` one-loop generator for the matrix elements [31].

`HiggsPair` describes leading-order Higgs boson pair production, either in the Standard Model or in its $D = 6$ effective field theory extension. The original implementation was described in [7] and its $D = 6$ EFT extension was examined in detail in [59].

`HiggsPairOL` describes SM Higgs boson pair production, with the optional use of Higgs–Higgs+one jet matrix elements merged to the parton shower via the MLM method. See [60] for a detailed description.

8 Sample results

With so many new features, it is impossible to show the full spectrum of results that have been improved, but in Figs. 1, 2, 3 and 4 we show a small sample.

The Monte Carlo results shown are from `Herwig++` version 2.7 using leading-order plus parton shower simulation and from `Herwig` 7.0 with the angular-ordered parton shower ($\text{LO} \oplus \text{PS}$), the angular-ordered parton shower supplemented by the internally implemented `Powheg` correction, which includes QCD and QED corrections for the case of $e^+e^- \rightarrow q\bar{q}$ ($\text{QCD} \otimes \text{QED} \otimes \text{PS}$), by the automatically calculated by `Matchbox` subtractive (MC@NLO -type) matching ($\text{NLO} \oplus \text{PS}$) and multiplicative (`Powheg`-type, $\text{NLO} \otimes \text{PS}$) corrections and, finally, the dipole shower supplemented by a subtractive matching to NLO cross sections ($\text{NLO} \oplus \text{Dipoles}$).

In Fig. 1, we show the most well-studied event shape from the LEP era, the thrust distribution, in comparison with data from the ALEPH collaboration [61]. A long-standing prob-

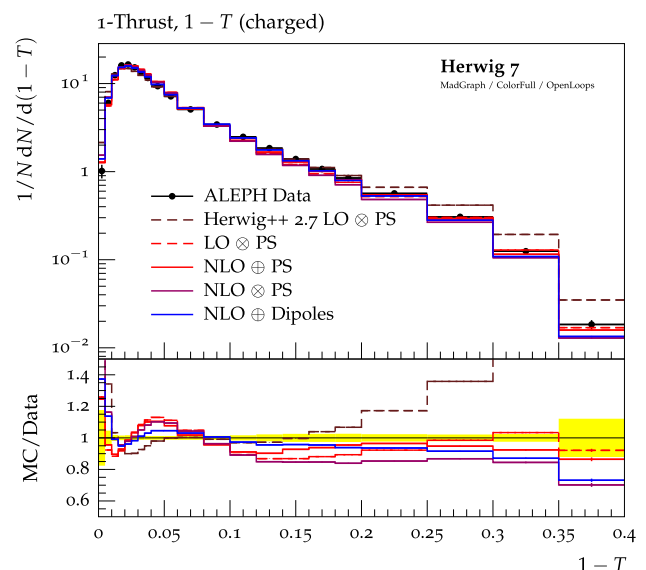


Fig. 1 The thrust distribution in e^+e^- annihilation at $\sqrt{s} = M_Z$, in comparison with ALEPH data [61]

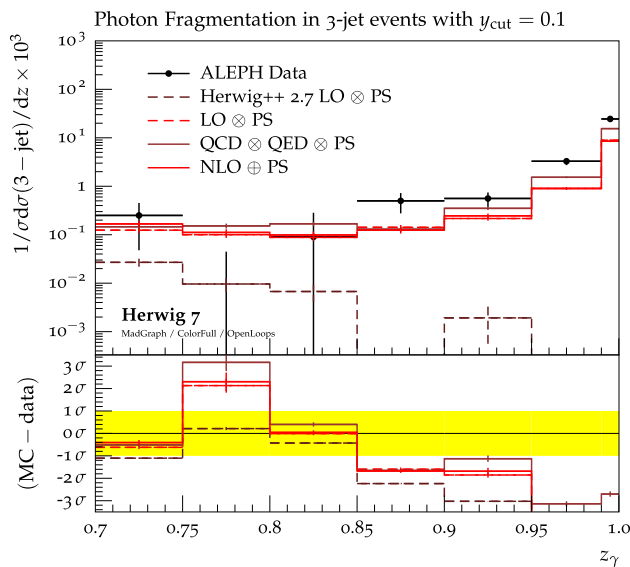


Fig. 2 The distribution of photon-jet energy fraction in three-jet e^+e^- events at $\sqrt{s} = M_Z$ defined with a cutoff in the k_\perp algorithm of $y = 0.1$ in comparison with ALEPH data [62]

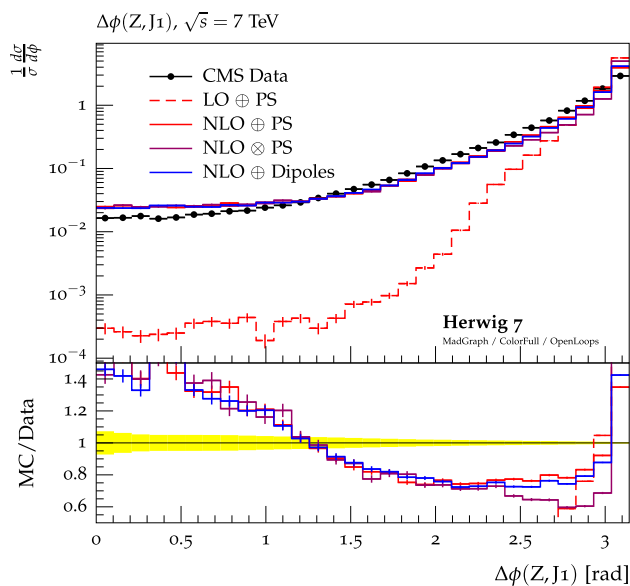


Fig. 3 The distribution of separation in azimuthal angle between the Z boson and the hardest jet in Z + jets events in pp collisions at $\sqrt{s} = 7$ TeV in comparison with CMS data [63]

lem of Herwig++ producing too many very hard events, whether or not NLO matching was used, is seen to have been solved by the improvements to the angular-ordered shower algorithm. All of the variants of NLO matching then give a similar description of the data, with the dipole shower giving a somewhat better overall description.

In Fig. 2, the effect of the inclusion of photon emission in the angular-ordered parton shower is shown. Events at $z_\gamma = 1$ are isolated photons (“jets” for which all of the jet energy is carried by a single photon), while events at lower

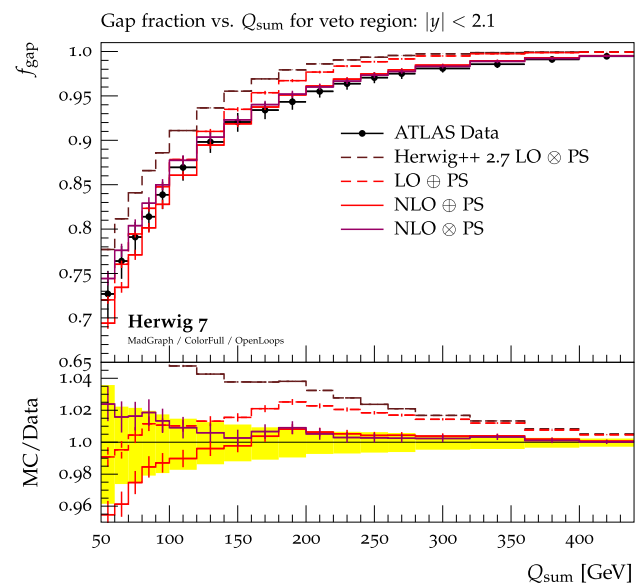


Fig. 4 The fraction of events that have less than Q_{sum} transverse energy in the rapidity region $|y| < 2.1$ in top quark–antiquark events in pp collisions at $\sqrt{s} = 7$ TeV in comparison with ATLAS data [64]

z_γ come from hard collinear photon emission from the final state quark jets. We see clearly that the results from Herwig++ have no component at large z_γ at all, while all of the Herwig 7.0 variants are much closer to the data with that including matching to NLO QED as well as QCD giving the best agreement. QED radiation within the dipole shower is subject to ongoing development and will be available in a future release.

In Fig. 3 we turn to results for Z + jets events at the LHC. We show the distribution of separation in azimuthal angle between the Z boson and the hardest jet. The region $\Delta\phi \sim \pi$ corresponds to leading order kinematics, in which the Z boson gains its transverse momentum by recoiling against a single hard parton, whereas the broad spectrum of events down to $\Delta\phi = 0$ corresponds to events in which the Z boson recoils against two or more jets. The need for NLO corrections is clearly seen. An important cross-check of the two different automated NLO matching schemes and the two different shower algorithms both using subtractive matching can also be seen.

Finally, in Fig. 4 we show the jet activity in N events at the LHC, as revealed by the gap fraction, i.e. the fraction of events for which the sum of the transverse momenta of all additional jets in the prescribed rapidity region is less than Q_{sum} . Herwig++ 2.7 is seen to have far too little jet activity (too many gap events). While Herwig 7.0 with the shower alone is somewhat closer to the data at small Q_{sum} , a clear deficit is seen for hard jet events at high Q_{sum} , while both the NLO matching schemes describe the data well.

This is of course just a very small selection of the large number of distributions that have been checked against data

in the final preparations of Herwig version 7.0, and more will be shown for specific processes in a series of forthcoming papers.

9 Summary and outlook

We have presented version 7.0 of the Herwig event generator, based on previous Herwig++ development and the experience gained with the HERWIG event generator. The new program features significant improvements as compared to both the Herwig++ 2.x series and the HERWIG 6 event generator, amongst them a powerful framework for NLO calculations and a number of improvements to both shower modules. Several accompanying publications containing detailed coverage of both physics and technical aspects will follow in due course, as well as an updated large and detailed manual to replace [2]. A completely new documentation system is already in place for Herwig 7 to allow the user to exploit the full capability of the new program. The methods and code developed within this release will also form the basis for ongoing and future development such as multijet merging at both leading and next-to-leading order, and electroweak corrections.

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